Ten Years of Millisecond Pulsar Timing at Kalyazin

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“Time”

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(Tver' region, Russia -37.65⁰ EL; 57.33⁰ NL).

Binary pulsars: J0613-0200, J1020+10, J1640+2224, J1643-1224, J1713+0747, J2145-0750, as well as isolated pulsar B1937+21, are belong to Kalyazin Pulsar Timing Array (KPTA).

The Backer's pulsar B1937+21 is being monitored at Kalyazin observatory (PRAO, Lebedev Phys.Inst., Russia-0.6 GHz) and Kashima space research centre (KSRC, NICT, Japan-2.2 GHz) simultaneously from 1996.

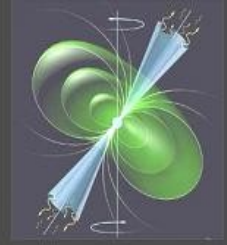
Main aim is:

a) to study Pulsar Time and to establish long life space ensemble of clocks could be alternative to atomic standards;

b) to detect gravitational waves extremely low frequency belong to the Gravity Wave Background –

Radio Telescope RT-64 (Kalyazin, Russia)

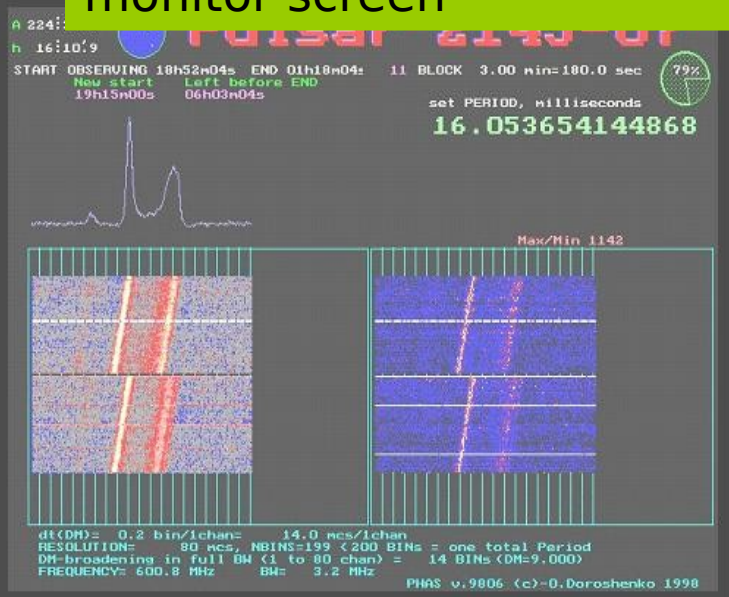
Main reflector diameter	64 m
Secondary reflector diameter	6 m
RMS (surface)	0.7 mm
Feed – Horn (wideband)	5.2 x 2.1 m
Frequency range	0.5 – 15 GHz
Antenna noise temperature	20K
Total Efficiency (through range)	0.6
Slewing rate	1.5



pulsar

Radio Telescope RT-64 (Kalyazin)

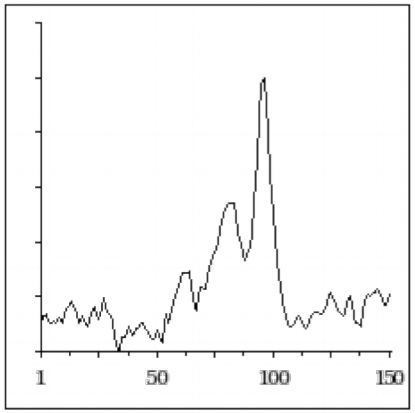
Integrated pulse profile of PSR J2145-0750 on monitor screen


START OBSERVING 18h52m04s END 01h18m04s 11 BLOCK 3.00 min=180.0 sec
New start Left before END
19h15m00s 06h03m04s
79%
set PERIOD, milliseconds
16.053654144868
Max/Min 1142
dt(DM)= 0.2 bin/ichan= 14.0 mcs/ichan
RESOLUTION= 80 mcs, NBINS=199 (200 BINs = one total Period
DM-broadening in full BW (1 to 80 chan) = 14 BINs (DM=9.000)
FREQUENCY= 600.8 MHz BW= 3.2 MHz
PHAS v.9806 (c)-O.Doroshenko 1998

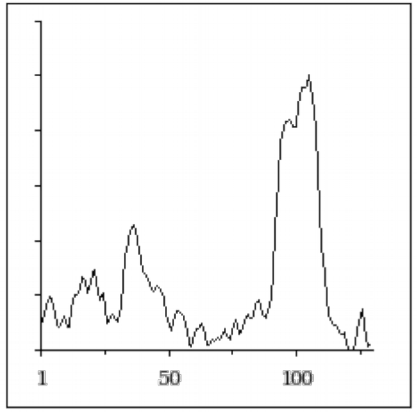
Local time service facilities and filter-bank

Mean Pulse Profiles of Kalyazin Pulsar Timing Array (KPTA) at 600 MHz by 64-m dish and filter-bank receiver

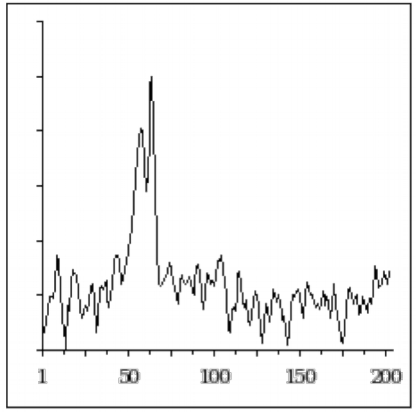
J0613-0200
P=3,1 ms, P_b=1,2 d, DM=38,7911
S=10,5 mJy, $\Delta t = 20$ μs, $T_{obs.} = 60$ min.



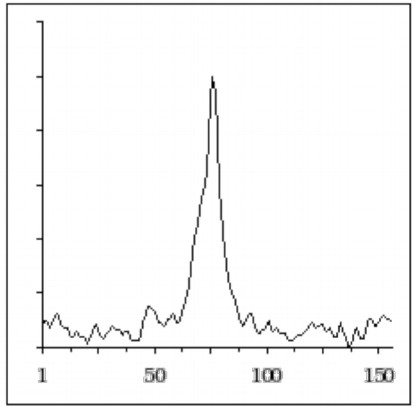
J1012+5307
P=5,2 ms, P_b=14,5 hrs, DM=9,0205
S=14 mJy, $\Delta t = 40$ μs, $T_{obs.} = 120$ min



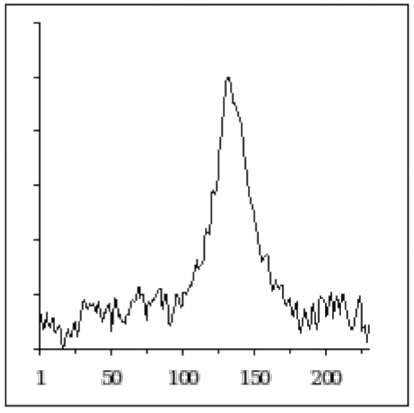
J1022+1001
P=16,5 ms, P_b=7,8 d, DM=10,2722
S=11 mJy , $\Delta t = 80$ μs, $T_{obs.} = 60$ min



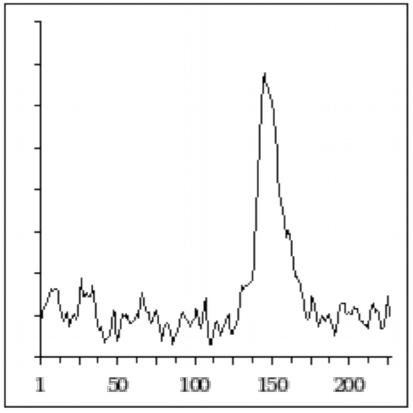
J1640+2224
P=3,2 ms, P_b=175 d, DM=18,415
S=25 mJy , $\Delta t = 20$ μs, $T_{obs.} = 80$ min



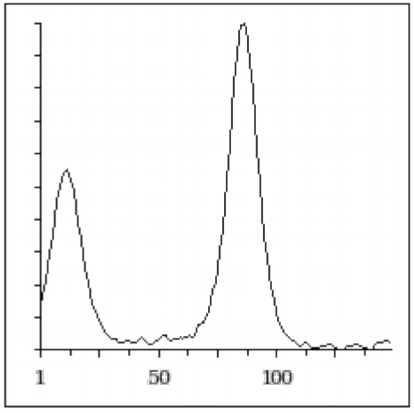
J1643-1223
P=4,6 ms, P_b=147 d, DM=62,404
S=26 mJy, $\Delta t = 20$ μs, $T_{obs.} = 60$ min



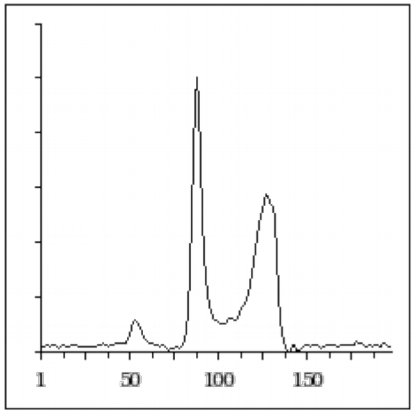
J1713+0747
P=4,6 ms, P_b=67,8 d, DM=15,9907
S=16 mJy, $\Delta t = 20$ μs, $T_{obs.} = 120$ min



B1937+21
P=1,6 ms, DM=71,044
S=100 mJy , $\Delta t = 10$ μs, $T_{obs.} = 30$ min

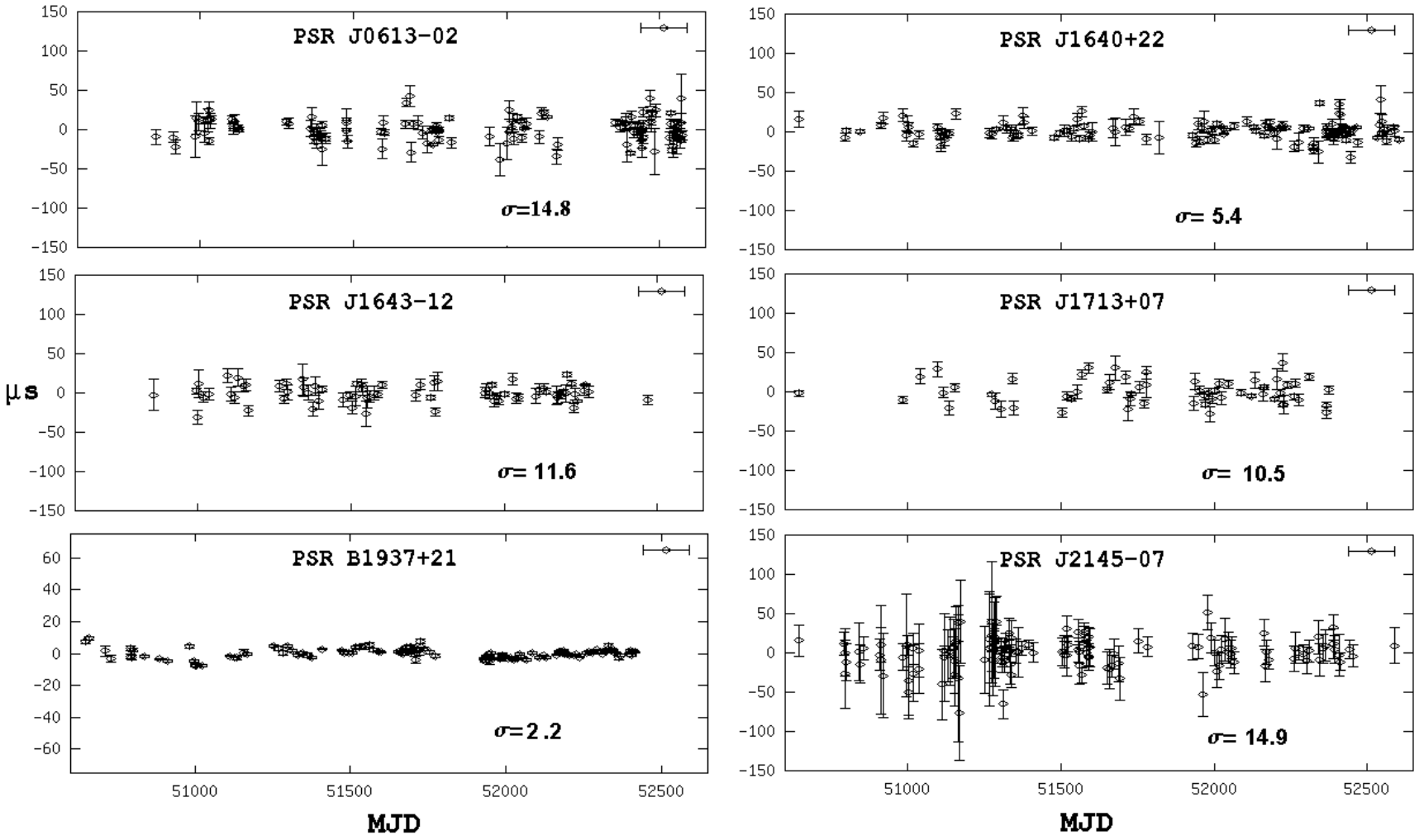


J2145-0750
P=16 ms, P_b=6,8 d, DM=9,000
S=30 mJy , $\Delta t = 80$ μs, $T_{obs.} = 40$ min

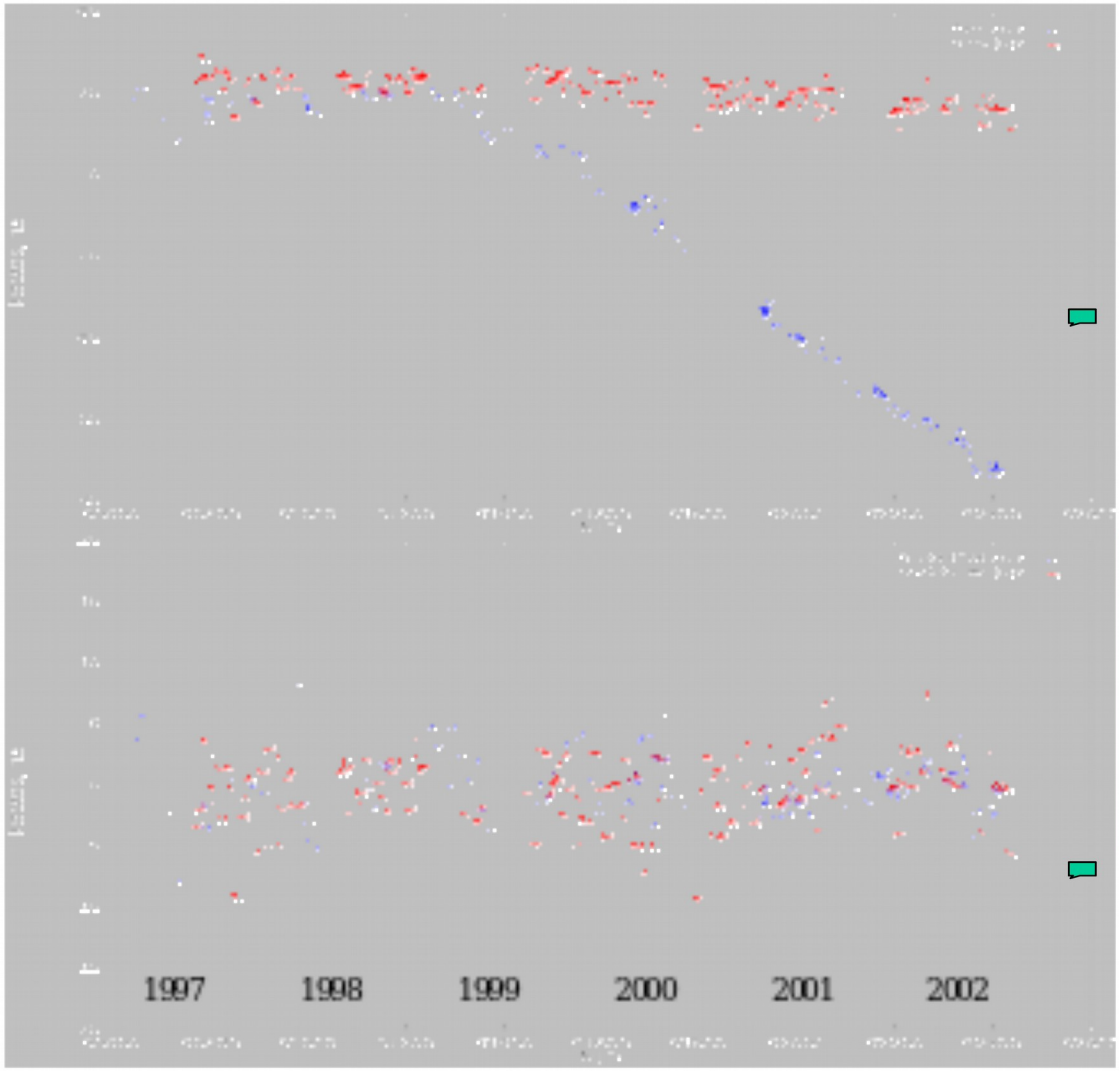


Pulsars profiles at 600 MHz ($\Delta f = 3,2$ MHz , 2 polarization).

Residuals of Millisecond Pulsars :B1937+21, J0613-0200, J1640+2224, J1643-1224, J1713+0747, J2145-0750



Joint Kalyazin-Kashima pulsar 1937+21 timing

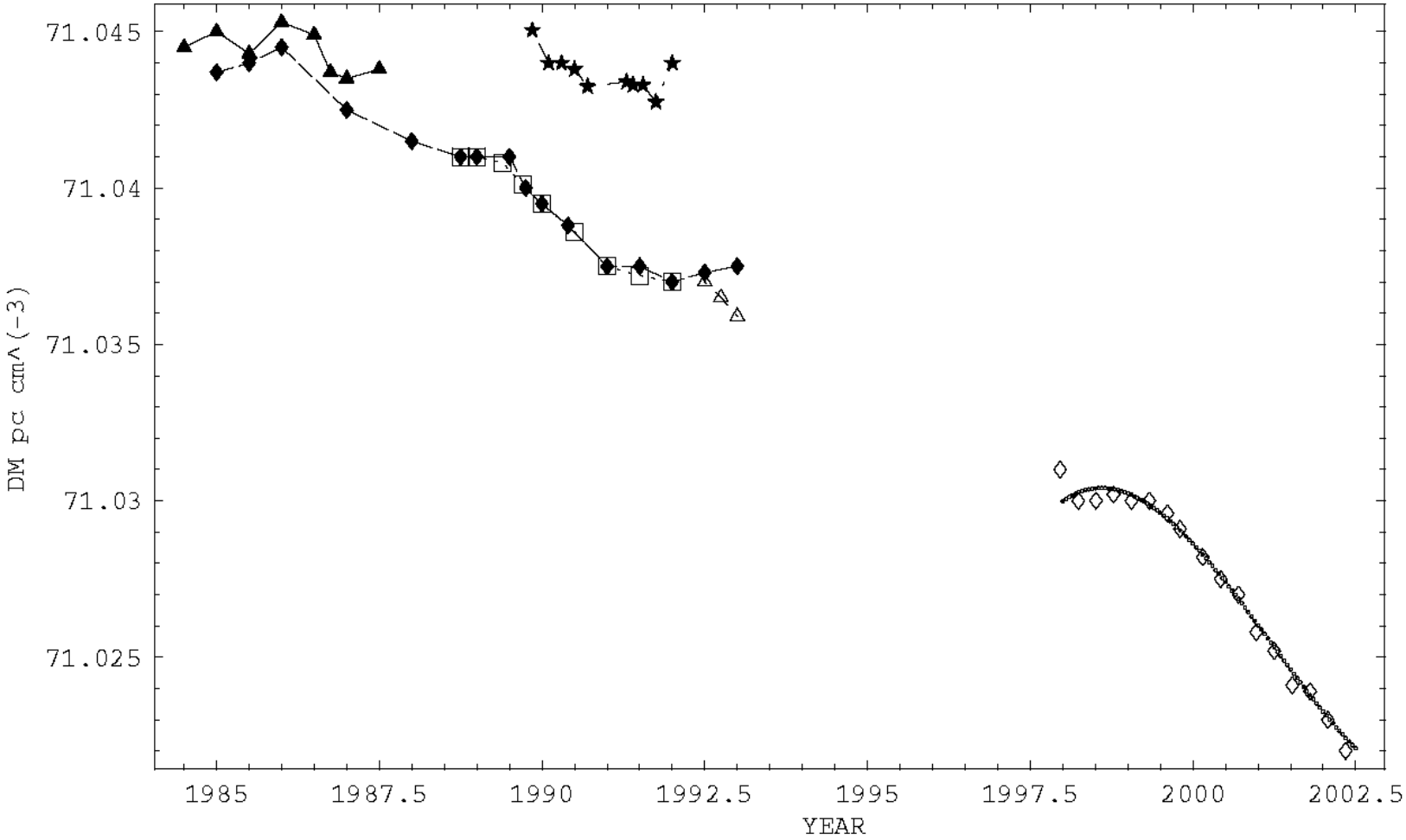


Kashima – 2,3 GHz
Kalyazin – 0,6 GHz
$DM_{1997} = 71{,}031$
$DM_{2002} = 71{,}021$

Residuals before correction for secular DM variations to B1937+21

Residuals after correction for secular DM variations to B1937+21
RMS = 1,8 мкс
$\Delta f/f \sim 9 \cdot 10^{-15}$

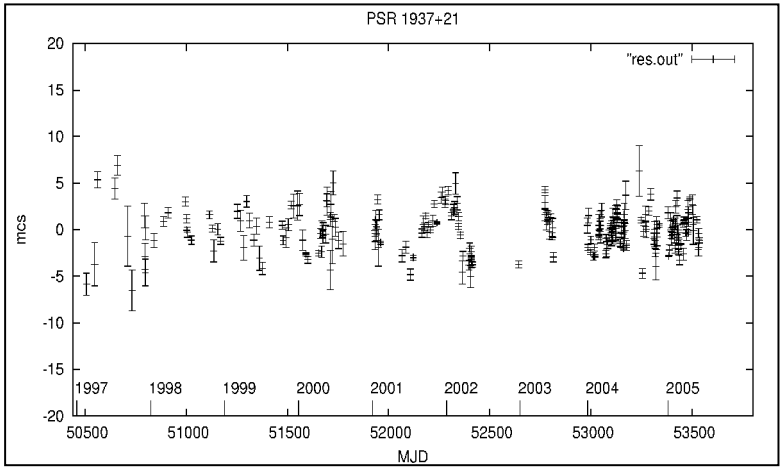
Ilyasov, Imae, Hanado, Oreshko, Potapov, Rodin, Sekido// Astron. Lett. Sov. v.31, p.30 (2005)

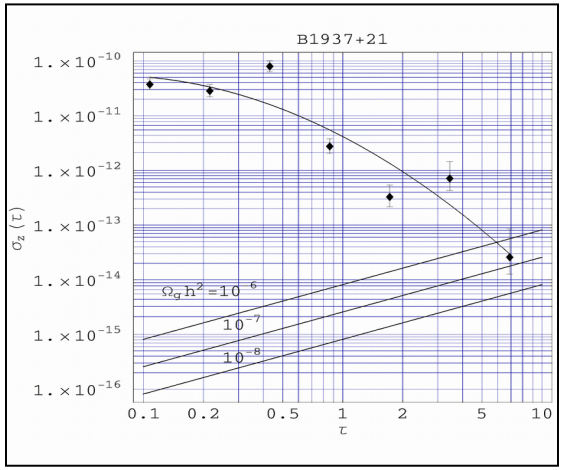


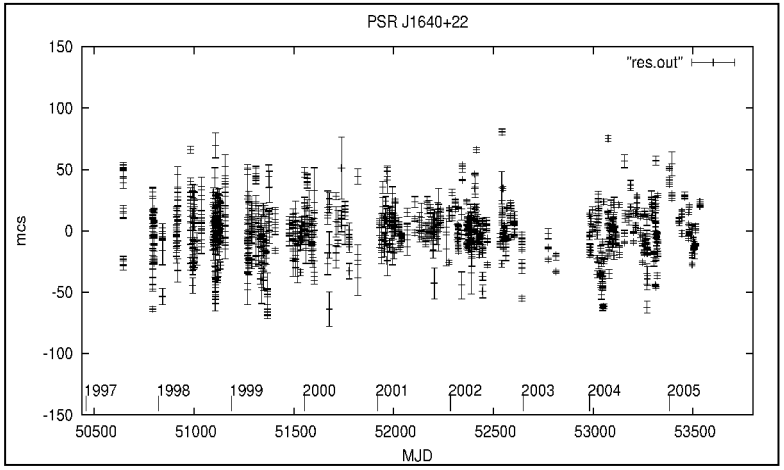
Rawley, Taylor, Davis, 1988, 1.4 - 2.4 GHz
Ryba., 1991, 1.4 - 2.4 GHz
Backer et al., 1993, 0.8 - 1.33 GHz
Kaspi, Taylor, Ryba 1994, 1.4 - 2.4 GHz
Cognard et al., 1995, 1.28 - 1.7 GHz
Kalyazin-Kashima, 2003, 0.6 - 2.3 GHz, straight calculation of DM (see Fig.3a)
Kalyazin-Kashima, 2003, 0.6 - 2.3 GHz, polinomial fit of DM (see Fig.3c)

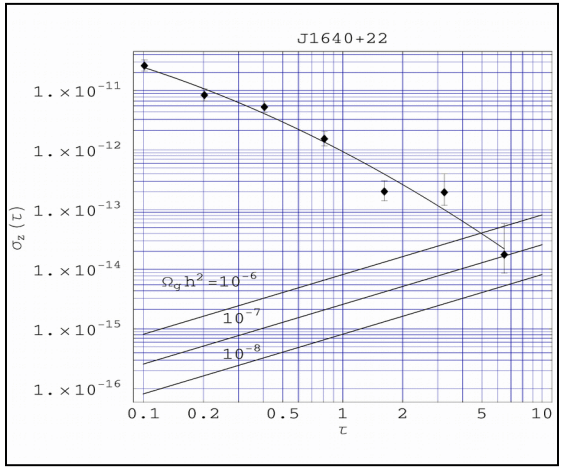
DM decreases with the averaged rate about -0.0012±0.0001 pc cm^(-3)/yr

LONG TIME INTERVAL RESIDUALS and ALLAN VARIANCE of PSR: J1640+2224, B1937+21 from KALYAZIN TIMING



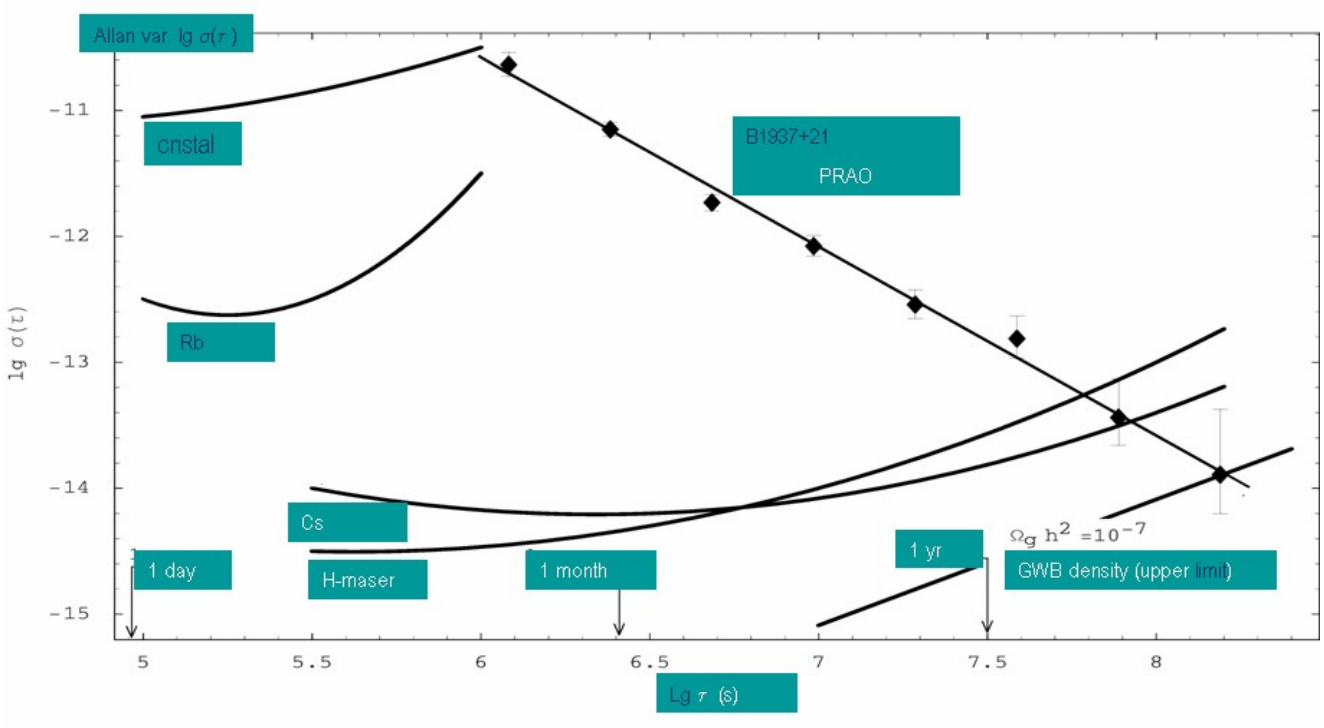






Residuals and Allan Variance of PSR : B1937+21 (upper),J1640+2224
(Kalyazin timing at 0.6 GHz)

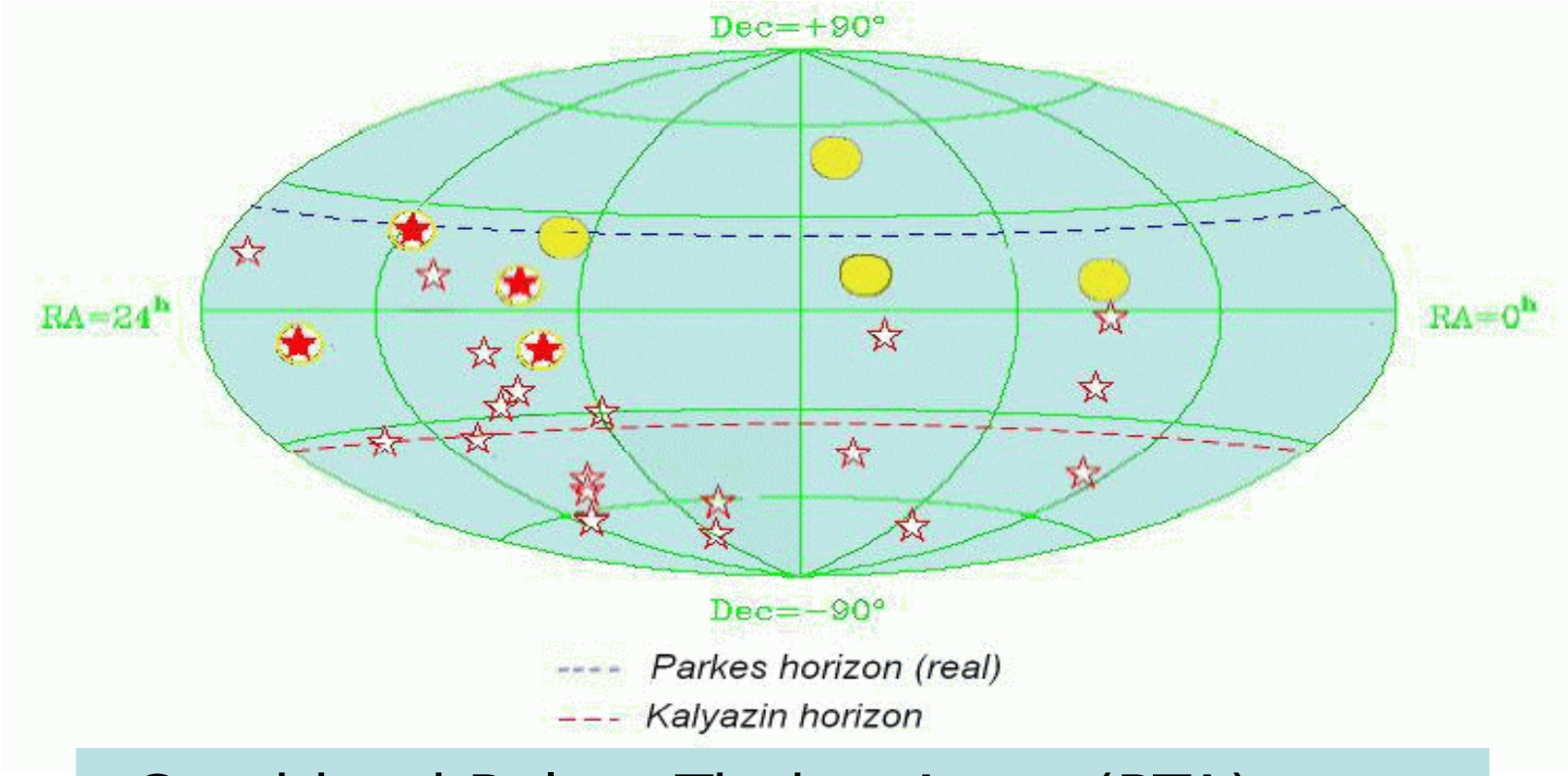
Allan Variance of Millisecond Pulsar B1937+21 and other Time Standards



After ten years monitoring of B1937+21 its timing noise is looking as “white phase noise” with RMS about 1.8 μs.(Fractional instability is about 6.10^{-15}). After these data and timing results of binary pulsar J1640+2224 gravitational natural GWB upper limit should be reduced till to less than $\Omega gh2 < 10^{-7} - 10^{-9}$.

Secular changes of DM toward millisecond pulsar B1937+21

Millisecond Reference Pulsars Round the Sky Distribution



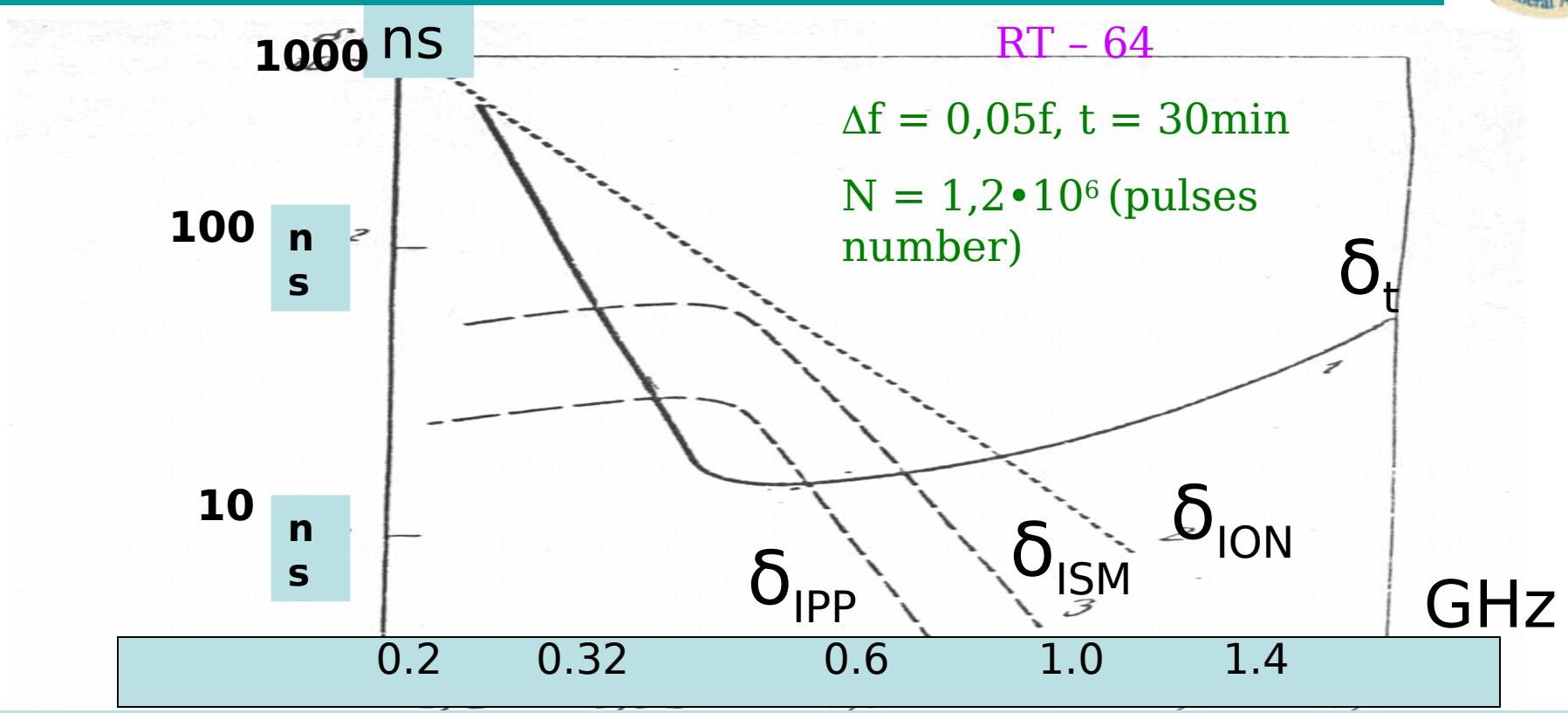
Combined Pulsar Timing Array (PTA):

Kalyazin

(ITCRF - ?proto frame?)

Parkes

RMS of TOA Measurement of Millisecond Pulsar B1937+21



δ_{IPP} - interplanetary plasma

δ_{ISM} - interstellar medium

δ_{ION} - ionosphere

δ_t – total RMS

(Ilyasov Yu. et al.1989, Lebedev Phys. Inst. Proceeding)

Preferred pulsars for Timing Array

PSR	P ms	Pdot 10^{-15} s/s	P_b day	DM pk cm^{-3}	S_{400} mJy	S_{600} mJy	S_{1400} mJy	S_{3000} mJy	α spectral index
B1855+09	5.3625	1.78 10^{-5}	12.327	13.309	31	(16.3)	4.3	1.5	-1.6
B1937+21	1.5577	1.05 10^{-4}	---.	71.040	240	(100)	16	4.0	-2.2

Next bands are allocated to radio astronomy in decimeter wavelengths range (Radio Regulations):

406.10 - 410.0 MHz (Primary allocation (P));

608.00 - 614.0 MHz ((P) - Region 2 & Secondary (S) - Region 1));

1400.0 - 1427.0 MHz ((P) and Passive (Pas));

2690.0 - 2700.0 MHz ((P) &(Pas)).

Recommended bands for Pulsar Timing could be: **1400 - 1427** MHz

Synchronous Integration Detrimental Threshold Level ΔP_{sa}

$$\Delta P_{sa} \leq 0.1 kTB\sqrt{\frac{N}{B\tau}}$$

T-system noise temperature, **B**-bandwidth, **k-** Boltzmann's constant,

N-integration cycle number, **τ -** time constant.

Detrimental impulse interference level ΔP_{peak}, acting onl

period P ! $D = t/P$

$$\Delta P_{peak} \leq \frac{kT}{4P}\sqrt{\frac{Bt}{D}}$$

t - integration time of observation (N= t/P)

Spectral flux density of detrimental synchronous impulse interference **ΔS peak :**

$$\Delta S_{peak} B = \frac{4\pi \Delta P_{peak}}{\lambda^2}$$

Threshold Impulse Interference Level

PSR	P ms	f MHz	B MHz	T=TA+TR K	Impulse interference			Continuous interference
					Pulsenterference ΔPpk (dBW)	Flux-Density $\Delta SpkB$ (dB(W/m2	Spectral Flux-Density ΔSpk (dBW/(m2 Pz)	Spectral Flux-Density ** ΔSm (dBW/(m2 Hz)
B1855+09	5.3621	408	3.9	203.0	-127.5	-126.1	-132.7	-137.7
		611	6.0	112.0	-129.1	-127.4	-134.2	-139.2
		1413	27.0	26.4	-132.1	-129.6	-137.0	-142.0
		2695	10.0	21.3	-135.2	-132.2	-139.2	-144.2
B1937+21	1.5578	408	3.9.	151.0	-123.4	-122.0	-129.5	-134.5
		611	6.0	93.0	-124.6	-122.9	-129.7	-134.7
		1413	27.0	24.1	-127.2	-125.8	-133.2	-138.2
		2695	10.0	20.8	-130.0	-127.0	-134.0	-139.0
J1640+2224	3.1633	408	3.9	92.0	-128.6	-127.2	-133.8	-138.8
		611	6.0	72.0	-128.7	-127.0	-133.8	-138.8
		1413	27.0	21.4	-130.8	-128.4	-135.8	-140.8
		2695	10.0	20.3	-133.1	-130.1	-137.1	-142.1
J1713+0750	4.5701	408	3.9	130.0	-128.7	-127.3	-133.9	-138.9
		611	6.0	85.0	-128.9	-126.3	-133.1	-138.1
		1413	27.0	23.1	-130.4	-127.9	-135.3	-140.3
		2695	10.0	20.6	-133.1	-130.1	-137.1	-142.1

** Number of cycles **N = t/P**; integration time **t = 3000 s**; time constant τ **= 0.01 P; syncronous pulse interference D**

Signal to Noise Ratio (SNR) Pulsars of Timing Array

(**Aef** = 2000 sq.m, **t observ**. = 3000 s , **Tsyst** (previous Table))

PSR	**P** ms	**f** MHz	**B** MHz	$\mathbf{T_s}=(T_A+T_R)$ K	**S** mJy	**SNR**
B1855+09	5.3621	408	3.9	203.0	31	12.0
		611	6.0	112.0	(16.3)	14.4
		1413	27.0	26.4	4.3	33.6
		2695	10.0	21.3	1.5	8.8
B1937+21	1.5578	408	3.9.	151.0	240	124.6
		611	6.0	93.0	(100)	104.5
		1413	27.0	24.1	16	136.9
		2695	10.0	20.8	4.0	24.1
J1640+2224	3.1633	408	3.9	92.0	37	31.5
		611	6.0	72.0	(16)	21.6
		1413	27.0	21.4	3	28.9
		2695	10.0	20.3	0.7	4.3
J1713+0750	4.5701	408	3.9	130.0	36	21.7
		611	6.0	85.0	(16)	18.3

CONCLUSION

- One of the most appropriate pulsars now are B1937+21, J1640+2224, J1713+0750 and B1855+09. They can be used as high-stable reference space clocks with the final goal of providing a new long – term stable time-scale.
- Most of leading radio astronomical observatory in the world now are involved in pulsar timing (Arecibo, Jodrell Bank, Kalyazin, Kashima, Medone, NRAO GBT, Parkes).
- High precision timing observations of reference millisecond pulsars, assigned for precision timekeeping as space astronomical reference clocks, can be made in preferred frequency band, allocated for the radio astronomy service band 1400-1427MHz, and either 400-406 or 608-614 MHz.
- The detrimental threshold level for precise pulsar timing are the same which defines by Recommendation ITU-R for single-dish continuum observations.
- Long-term timing monitoring of very stable reference pulsars by the largest radio telescopes in the world should be encouraged with the goal to provide the International Time Celestial Reference Frame (ITCRF), in particular for space navigation.
- Time scale based upon reference pulsars could be established to